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RECENT STABILITY COMPARISONS WITH THE JPL LINEAR TRAPPED ION FREQUENCY STANDARDS[1]

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Abstract

The $^{199}Hg^+$ research frequency standards LITS-1 and LITS-2 were developed to provide continuous, reliable, high stability performance. For simplicity, a ^{202}Hg lamp is used for state selection and a helium buffer gas for ion cooling. In a preliminary 9 day comparison between the trapped ion standards, the Allan deviation was $\sigma_y(\tau)= 1\times10^{-13}/\tau^{1/2}$ and a fractional frequency stability of 6×10^{-16} measured for averaging times greater than 10^5 seconds. A 40 day comparison of LITS-2 against an auto-tuned H-maser referenced to UTC-NIST puts an upper limit on long term drift of LITS-2 of $1.2(1.4)\times10^{-16}$/day.

Introduction

Trapped ion frequency standards show great promise towards fulfilling several intermediate and long term frequency and timing needs. Ion trap based standards have the main advantage that the ion (atomic oscillator) is confined only by electromagnetic fields. Perturbations due to collisions are greatly reduced and ions can in principle be held indefinitely allowing for extremely long interrogation times. The $^{199}Hg^+$ ion is particularly well suited for frequency standards because the large mass and ≈40.5 GHz ground state hyperfine splitting reduce sensitivity to thermal and magnetic variations. Research standards LITS-1 and LITS-2 were developed to provide continuous high stability operation. These linear ion trap [1] standards (LITS) use a ^{202}Hg lamp to generate 194 nm light for optical state selection [2] and helium buffer gas to cool the ions to near room temperature [3].

The microwave $^2S_{1/2}(F=0,m_F=0)$ to $^2S_{1/2}(F=1,m_F=0)$ hyperfine transition of $^{199}Hg^+$ has a measured $Q>2\times10^{12}$ [5]. Good signal to noise is achieved with as many as 3×10^7 ions in a linear ion trap. Several local oscillators (LO) have been used, including a good quartz crystal, a H-maser, or the Superconducting Cavity Maser Oscillator (SCMO) [4,5,6]. Short term performance of $7\times10^{-14}/\tau^{1/2}$ [6] is obtained using a hydrogen maser as the local oscillator. With improvements to the optics configuration, we estimate the lamp based system is capable of $4\times10^{-14}/\tau^{1/2}$.

Measured environmental sensitivity [6] indicate that an order of magnitude improvement compared to H-maser stability is possible with regulation levels still less stringent than for masers. Because a large number of mercury ions are confined at room temperature, the second order Doppler shift is the leading perturbation that will dictate the stability floor and the system accuracy. Current frequency accuracy is about 10^{-13}, though with an ion temperature measurement accurate to 1% [7] overall accuracies of 10^{-14} should be possible. A cryogenic, laser based $^{199}Hg+$ standard is currently under development at NIST [8]. This approach uses only a few ions which limits signal to noise, but has the potential of high absolute accuracy with long averaging times. Both approaches will benefit if current research to develop an ultra-violet diode laser capability is successful (see e.g. [9]), The JPL standards would achieve even better short term stability, and laser cooling would become much more practical.

In this paper, we report the first 9 day stability comparison between the JPL Hg+ trapped ion research standards LITS-2 and LITS-1. This comparison demonstrates stabilities well into the 10^{-16} range for averaging times longer than 100,000 seconds (Fig. 1). We also report a 40 day stability comparison between LITS-2 and two H-masers.

Long Term Stability and Environmental Sensitivity

The limiting long term stability depends on the frequency sensitivity of the hyperfine transition to confinement and environmental perturbations. Typical operating conditions, frequency offsets, and measured sensitivities have been previously reported [6]. The accuracy

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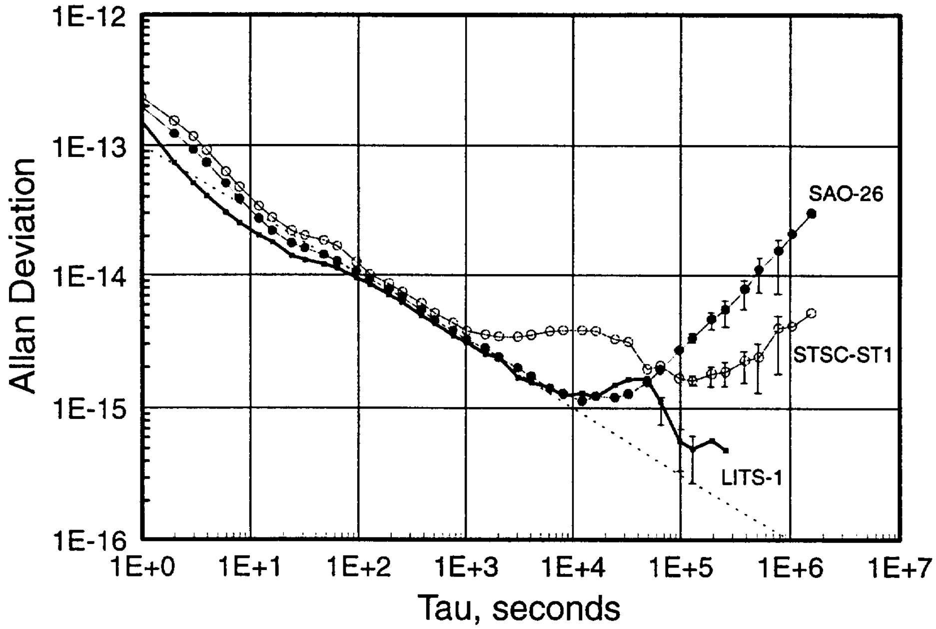

Figure 1: Forty day stability comparison of the Hg+ standard LITS-2 against (a) SAO-26 H-Maser, (b) STSC ST-1 Auto-tuned H-Maser, and (c) a nine day comparison against the Hg+ standard LITS-1.

and limiting stability of the trapped ion standards depends on how well these offsets are understood and held constant.

To measure the stability between the two $^{199}Hg^+$ standards each steers a separate VLG-11 [10] H-maser receiver (Fig. 2). These local oscillators consist of a good crystal oscillator phase locked to a common H-maser oscillator. Each LO is steered at approximately 20 second intervals based on the error signal determined by the microprocessor controlling the ion trap interrogation cycle. Both receivers provide a 100 MHz output and one is offset by 1 Hz. The 1 Hz beat is measured and the stability analyzed. As shown in Figure 2, the steered output of each LO is also compared against other available reference standards.

For this initial comparison both standards were operated with a 16 second microwave interrogation cycle and a performance of $1\times10^{-13}/\tau^{1/2}$. Figure 1 shows the Allan deviation of LITS-2 compared to three separate references, LITS-1, the H-maser SA0-26 [10], and the auto-tuned H-maser STSC-ST1 [11]. The SAO maser is useful for determining performance for averaging intervals less than 20,000. The STSC-ST1 maser has poorer short term stability, but is useful as a long term reference [12]. The STSC-ST1 maser is also independently compared to UTC-NIST via GPS to provide a reference to the international time scale.

The data shown in Figure 1 has no drift removed, though a $\sqrt{2}$ has been removed from the LITS-2 vs. LITS-1 comparison for averaging times greater than 20 seconds.

LITS-2 and LITS-1:

The stability between the two trapped ion standards reaches approximately 6×10^{-16} at 100,000 seconds. This point consists of 6 samples and the uncertainty is shown in figure 1. The peak at approximately 50,000 seconds resulted from a poor regulation circuit on LITS-1. This is made graphically clear in Figure 3 which shows the Allan deviation of each trapped ion standard compared against SAO-26. An oscillation is observed in the frequency residuals of both comparisons involving LITS-1. The oscillation is not present in LITS-2, which has better control electronics. In this preliminary 9 day measurement the differential drift between LITS-2 and LITS-1 is $3.2(2.7)\times10^{-16}$/day. This small drift correlates well with a known sensitivity and measured drift of the RF trapping potential of LITS-1 during the comparison. The long term drift of the SAO maser is measured independently by both LITS-1 and LITS-2 during the same time interval of $4.4(0.3)\times10^{-15}$/day and $3.7(0.6)\times10^{-15}$/day respectively. The drift rate of the maser changes over time (see also [12]). For the 40 day comparison between SAO-26 and LITS-2 (Fig. 1) the measured drift is $2.4(0.3)\times10^{-15}$/day.

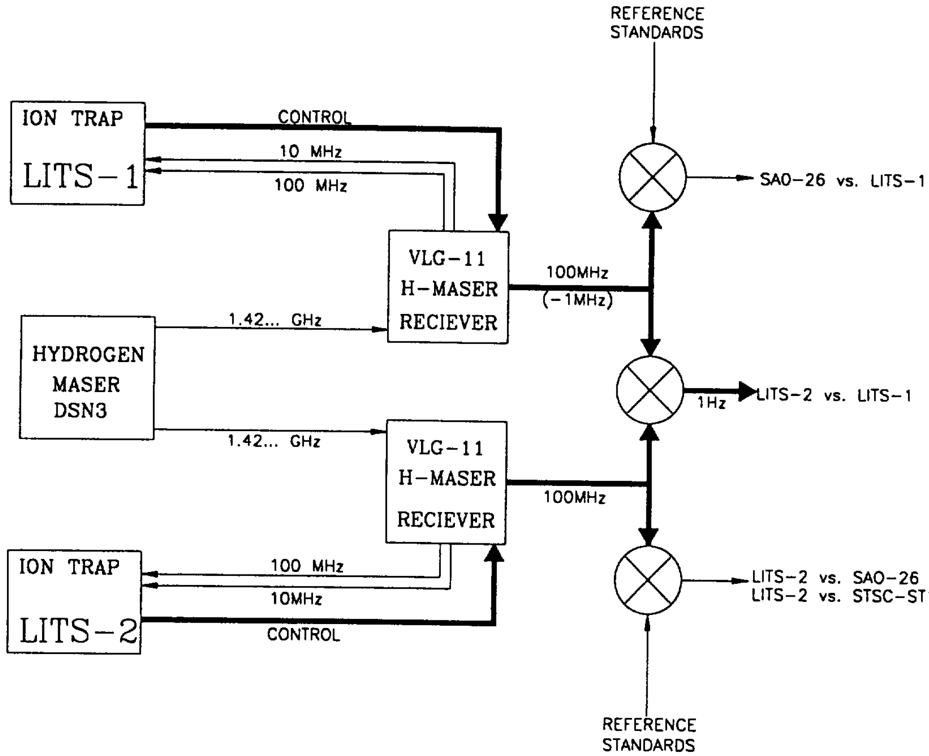

Figure 2: The measurement scheme used to compare the two trapped ion standards LITS-1 and LITS-2. Both Ion traps steer a separate VLG-11 H-maser receiver.

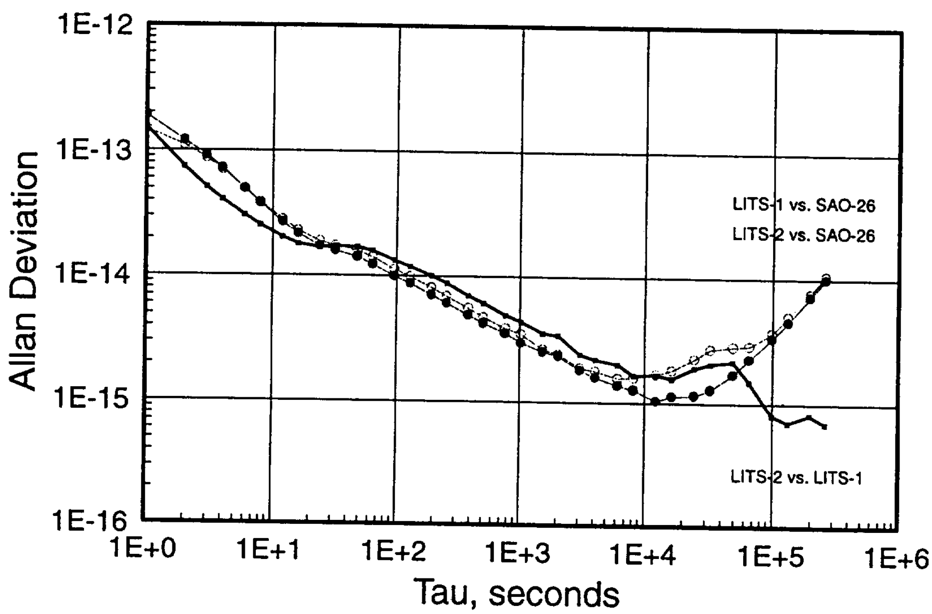

Figure 3: Nine day conparison between the Hg+ trapped ion standards LITS-2 and LITS-1. Both standards are also compared to the H-maser SAO-26 over the same time interval.

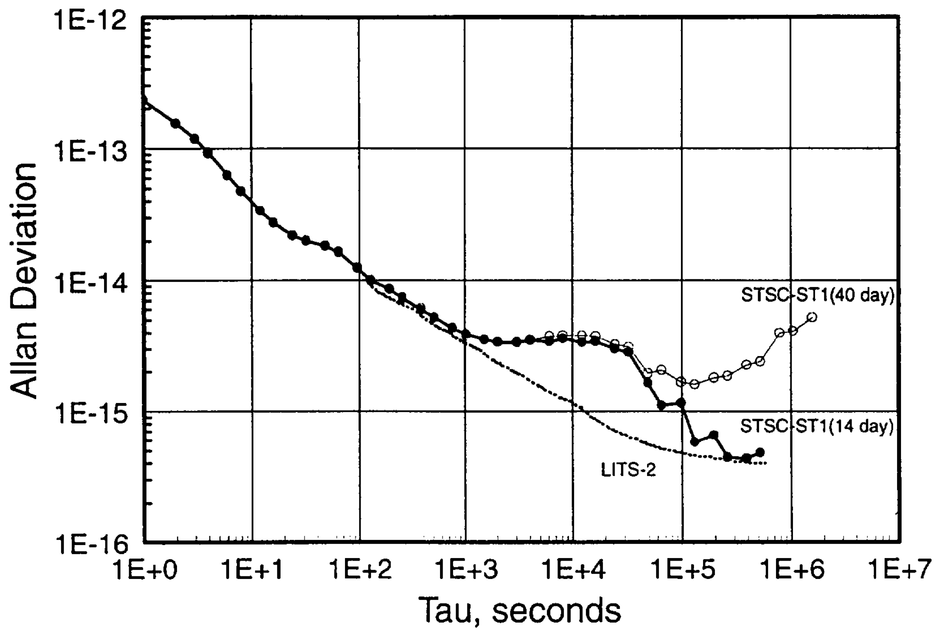

Figure 4: The Stability of LITS-2 compared against the H-maser STSC ST-1 for a selected 14 day period between frequency jumps in the H-maser. Also shown is the complete 40 day measurement.

LITS-2 and STSC-ST1:

In Figs. 1 and 4 the Allan deviation of a 40 day comparison between LITS-2 and the auto-tuned H-maser STSC-ST1 is shown. The differential drift between these two standards over this 40 day span is $4.7(1.6)\times10^{-16}$/day. A closer examination of the time residuals shows a large 10^{-14} frequency shift 10 days into the measurement. This shift can not be accounted for in LITS-2 and is apparently due to a frequency jump in the STSC-ST1 maser. This frequency change is confirmed in long term time residuals in GPS measurements comparing the STSC-ST1 H-maser to UTC-NIST. Similar frequency jumps a few times a year have also been reported elsewhere [12]. For the purpose of characterizing the stability of LITS-2, long term reference of the maser to UTC-NIST indicates stable reference windows between frequency jumps in STSC-ST1.

Figure 4 shows the Allan deviation for a two week interval of the 40 day comparison. During this time interval the frequency stability of the STSC-ST1 H-maser is particularly good as confirmed by the GPS comparison with NIST. In this 14 day comparison, the differential drift between LITS-2 and the STSC-ST1 maser is measured to be $1.2(1.4)\times10^{-16}$/day. For averaging times longer than 100,000 seconds this measurement is in agreement with the performance of LITS-2 as measured by LITS-1 (Fig. 1).

Electronic Improvements and Reducing Sensitivity With The Extended Linear Ion Trap (LITE)

Because of the low sensitivity to thermal and magnetic perturbations, averaging to 10^{-15} stability is accomplished with only minimal electronic control and isolation from environmental perturbations [6]. LITS-1 and LITS-2 are research laboratory standards and though portable, are not highly regulated. The data presented here was obtained with the standards thermally regulated to 0.05 C and a low field differential magnetic shielding factor of only 800. The trapping potentials are run "open loop" and the ion number is not actively servoed. Several improvements to the control electronics are currently under development which should allow the standards to average with characteristic $1/\tau^{1/2}$ behavior to near 1×10^{-16}.

In addition to relying on further electronic improvements for improved stability there are ways to reduce fundamental sensitivity and still maintain a practical, room temperature, lamp based system. An extended version of the linear ion trap (LITE) is currently under development [13] which takes advantage of the capability to easily move ions. By moving ions between two regions of a linear ion trap, the two often conflicting tasks of ion loading and optical state selection can be separated from the microwave interrogation region which requires an excellent magnetic environment. Moving the ions into a long interrogation region reduces the linear ion density without sacrificing signal to noise. This not only reduces sensitivity to second order Doppler perturbations but may allow operation at lower magnetic fields.

Conclusion

A second ^{199}Hg+ trapped ion frequency standard LITS-2, now under continuous operation, provides a capability for measuring stability beyond all existing frequency standards for averaging times longer than 20,000 seconds. In a recent frequency stability comparison between ion trap standards LITS-1 and LITS-2, each standard steered a separate VLG-11 hydrogen maser receiver demonstrating stabilities of 6×10^{-16} for averaging times up to 9 days. The Allan deviation of each standard was $\sigma_y(\tau)= 1\times10^{-13}/\tau^{1/2}$ with the differential drift measured to be $3.2(2.7)\times10^{-16}$/day. This remaining small drift is predominantly in LITS-1 and correlates well with a measured drift in the trapping potential. A 40 day comparison of LITS-2 against an auto-tuned H-maser referenced to UTC-NIST provides an upper limit on the drift of LITS-2 of $1.2(1.4)\times10^{-16}$/day.

With both standards operating at the previously demonstrated short term performance of $\sigma_y(\tau)=7\times10^{-14}/\tau^{1/2}$ a stability of 1×10^{-16} should be possible in 5×10^{5} seconds given sufficient magnetic shielding and stability in the control electronics. Measured environmental sensitivities indicate this can be accomplished with regulation still less stringent than for hydrogen masers. In addition, use of a new extended linear ion trap (LITE) configuration should further reduce remaining sensitivity to ion number and magnetic field fluctuations, allowing for even higher stabilities.

Acknowledgements

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